The Effectiveness of Nitrogen Recommendation Strategies for Corn in Creating Variable Rate Prescriptions Using Precision Agriculture Technologies

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Abstract

Nitrogen is one of the primary macronutrients required for plant growth, and is often the most limiting factor in plant nutrition. In corn production, nitrogen fertilizer must be applied in order to supplement the nitrogen that is available in the soil. Due to nitrogen's mobile nature in the soil, and the effect of temperature and rainfall on its availability to plants, it is difficult to predict the optimum rate that should be applied to reach yield potential while avoiding over-application and environmental risk from off-site movement. The Ohio State University Extension currently recommends using an economic optimum rate calculation to predict the optimum application rate. However, with the increasing use of precision agriculture technology that utilizes GPS to allow for site-specific management, there is an interest in using variable-rate technology to further optimize nitrogen applications. The objectives of this study are to describe the variability of optimum nitrogen rates across soil types and productivity zones, evaluate the effectiveness of prediction methods in identifying the optimal rate in each zone, and describe the ability of these prediction methods in developing variable-rate prescriptions. Five fields were selected as testing sites, with three replicated test blocks in each field. Test blocks were placed in high, medium, and low yielding zones in each field based on yield history. Utilizing test strips ranging from 0 to 220 pounds of nitrogen applied, the economic optimum rate was calculated after yield data was collected at harvest. Current Ohio State nitrogen recommendations, Tri-State fertilizer recommendations, Brookside Labs potential nitrogen analysis soil test, the pre-sidedress nitrogen soil test, normalized yield history, and estimated crop removal were all evaluated in their ability to predict optimum nitrogen rates.

Introduction

Nitrogen is one of the primary macronutrients required for plant growth, and is often the most limiting factor in plant nutrition. Nitrogen is available for uptake by plants when it is in the nitrate (NO_3^-) or ammonium (NH_4^+) forms. These can be supplied from several biotic and abiotic sources, with the largest source of corn nitrogen being supplied by manufactured fertilizers such as anhydrous ammonia, urea, or urea ammonium nitrate (UAN) (Lindquist, Evans, Shapiro, & Knezevic, 2010).

In recent years, the costs of these nitrogen fertilizers have increased, crop values have increased, and there have also been increasing concerns of agriculture's role in nitrate pollution of water sources. In response to these issues, many farmers have begun adopting variable-rate technology (Diedrick, 2010). Relative to fertilizer application, this technology uses GPS signals to locate a tractor's position in a field. Using geo-referenced prescriptions that are loaded into a mobile computer in the tractor, the computer determines the fertilizer rate to be applied at the tractor's current position in the field, and adjusts the control valve on the applicator to apply the specified rate. As the tractor moves across the field into a zone that requires a different fertilizer rate, the application rate changes accordingly. This technology allows the correct amount of fertilizer to be applied to meet the needs of each specific area of the field (Chan, Schueller, Miller, Whitney, & Cornell, 2004).

However, because nitrate is an anion, it is unable to remain in the soil for long periods of time due to the negative charge of soil particles. Therefore, soil testing capabilities for nitrogen are limited due to the constantly varying nitrogen levels. In addition, it is difficult to determine the amount of nitrogen that is available from other sources such as previous legume crops or soil organic matter. The weather is also a major factor determining nitrogen availability. This makes it difficult to accurately create prescriptions for variable rate nitrogen applications (Diedrick, 2010).

Problem Identification and Justification

While modern precision farming equipment has the capability to apply nitrogen at varying rates throughout a field, there are few guidelines for creating variable-rate prescriptions. The Ohio State University Extension currently recommends nitrogen rates based on the prices of corn and nitrogen so that the maximum return per pound of nitrogen is reached (Mullen, 2006). Given the number of variables that play into nitrogen's behavior in the soil, (such as application timing, temperature, rainfall, type of fertilizer, method of application) this does seem to be the most effective way to provide statewide guidelines for nitrogen application.

However, given the significant variability in soil types and crop growing conditions even within a single farm, there seems to be an opportunity for variable-rate applications of nitrogen to allow for more efficient use of nitrogen and more uniform crop yields. Recent increases in fertilizer costs and corn prices have made the importance of accurate fertilizer applications of farmers a top priority. In addition, recent water quality issues, such as algae blooms on Lake Erie, have prompted investigations looking at how agricultural fertilizer runoff contributes to the environmental problems. If variable rate applications can be utilized effectively, they will have the potential to place fertilizer more accurately, improve returns for farmers, and reduce the possibility of nitrogen entering waterways. This study evaluates varying nitrogen rates in different field conditions and tests the viability of certain methods of creating variable rate applications.

Objectives

The goal of this research is to explore the effectiveness of utilizing variable rate nitrogen applications to reduce input costs and increase yield, which can lead to increased profitability and a decreased probability of negatively affecting the environment through runoff and leaching of fertilizer. The research objectives are as follows:

- Determine the optimal rate of nitrogen that provides the highest net return on investment in each testing block under 2013 growing conditions.
- Describe the variability of optimal rates across varying soil types and productivity levels.
- Describe the effectiveness of several methods of predicting the optimal nitrogen rate prior to application.

Methods

Five fields located in Lucas County, Ohio were selected for this research. For each field, all available yield maps from previous years were collected. A yield map is created at fall harvest. As the crop was harvested, instantaneous yield was measured by the harvester's grain flow sensor and recorded each second. These data points are associated with a latitude and longitude value representing the harvester's location at the time that the measurement was taken. The data points are then mapped to form a yield map. Yield map availability ranged from one to five years of history, and represented past corn, soybean, and wheat crops. Table 1 outlines the yield history that was available for each field.

Table 1: Available yield history of fields used in this study

Field	**2008**	**2009**	**2010**	**2011**	**2012**
A	n/a	n/a	n/a	Soybeans	Wheat
B	Corn	Corn	Soybeans	Corn	Corn
C	n/a	n/a	n/a	Corn	Soybeans
D	n/a	n/a	n/a	Corn	Soybeans
E	n/a	n/a	n/a	n/a	Soybeans

Following collection, the yield maps for each field were used to create a normalized yield map using Farm Works precision agriculture software (Farm Works, Hamilton, IN, http://www.farmworks.com/). In the process of creating normalized yield maps, the software overlays a grid, made up of 10 foot by 10 foot squares, onto a yield map. The yield for each square is calculated based on the data points of the yield map that fall within or near each square. Each square's yield is compared to the field's average yield, and a new value is assigned to each square, expressing the square's yield as a percent of the field's average yield. This process is repeated with the yield map for each year. After a map is created for each year, the values from all of the years are averaged together for each individual square, creating one normalized yield map that represents all past yield history. These squares can be assigned colors to visually represent the trends in spatial yield variability. Appendix A contains the normalized yield maps for each field used in this study.

Since the software analyzes only one field at a time, the original normalized yield values must be corrected to account for variability in average yields across the different fields. For the purposes of this study, normalized yield was corrected by first calculating each field's performance relative to the overall yields on the farming operation for each crop. Using three years of yield history, a field productivity value was established representing that field's percent of average yield for the entire farming operation. All of the normalized yield values for each field were then corrected by multiplying by the field's percent of average farm yield. This correction places all normalized yield values on a single scale: percent of average farm yield.

Once these maps were created, they were used to select sites for test zones to be used in the study. Within each of the five fields, three zones were selected: one in a relatively high yielding area, one in an average yielding area, and one in a relatively low yielding area. The locations of test zones in each field are shown on the maps in Appendix A.

Within each zone, nine to twelve test strips were defined. Each strip was 30 feet wide and 180 feet long. However, the first and last 30 feet of each strip was used as a buffer zone, so that measurements were only taken from a strip that was 30 feet wide by 120 feet long. The strips were arranged in one of two formations. A horizontal formation consisted of one row of nine strips; where as a vertical formation consisted of two rows of six strips (twelve total). The formations were selected in order to maximize consistency of normalized yield value within each test zone. Figure 1 depicts the layout of each type of zone formation.

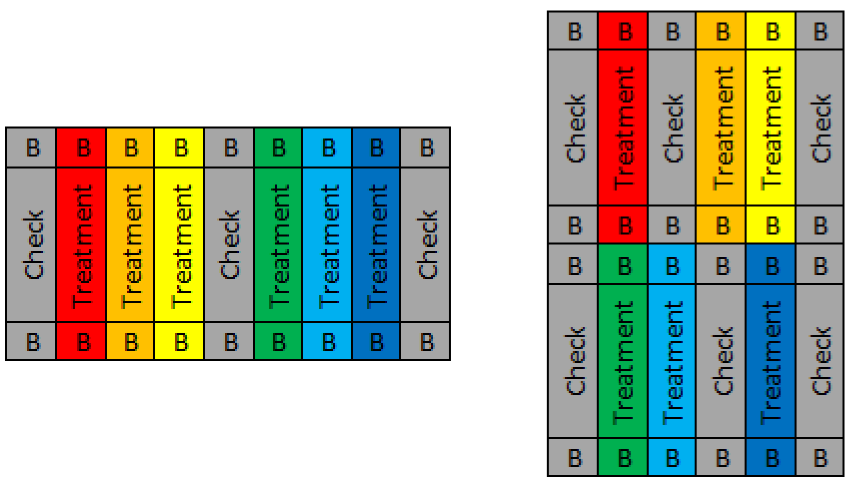

Figure 1: Layout of a horizontal zone formation (left) and vertical zone formation (right). Each strip is 30 feet wide by 120 feet long, with an additional 30 feet of buffer on each end. Buffer zones are indicated by a "B".

After the strips were laid out, nitrogen rates were assigned to each strip. The outermost strips and center strip were used as check strips and were assigned the same nitrogen rate as applied to the rest of the field. Horizontal formations contained three check strips where as vertical formations contained six check strips. The six remaining strips were randomly assigned nitrogen rates of 0, 50, 100, 140, 180, and 220 pounds of actual nitrogen per acre.

Prior to treatment, soil samples were gathered for use in evaluating optimal rate prediction methods. Eight soil cores were collected from each zone. Each zone's cores were combined and sent to Brookside Labs, Inc. of New Bremen, Ohio for analysis.

Once rates were assigned, the strips were compiled into a variable-rate nitrogen prescription. The nitrogen was applied as anhydrous ammonia (82% nitrogen) in a sidedress application during the last week of May at the V2-V3 growth stages. The variable-rate prescription allowed the treatments to be applied automatically throughout the field as the tractor and applicator crossed into each strip. The buffers on each end of the strips allowed the control valve time to adjust and arrive at the new rate before the applicator entered the center of the portion of the strip that would be measured. Following application, as-applied maps were used to verify application rates and account for any applicator error. The prescription maps used for each field can be found in Appendix A. In addition to the nitrogen applied in each treatment at sidedress, each field received 30 pounds per acre of nitrogen applied at planting as 28% urea-ammonium-nitrate and 10 pounds per acre of nitrogen applied in a broadcast application before planting as granular ammonium sulfate.

At harvest, yields were collected by a harvester equipped with a properly calibrated yield mapping system, which created yield maps in the manner as described previously. Using Farm Works software, all of the data points of the yield map located within each test strip (excluding the data points in the buffer zones) were averaged to determine the yield of each test strip. Using the recorded yields, a return value was calculated for each strip, by subtracting the cost of nitrogen from the value of the corn. In order to calculate the return values, corn was valued at $4.25 per bushel and anhydrous ammonia was valued at $910 per ton.

Response curves were then constructed for each zone. The return value was plotted as a function of the application rate. The application rates used were actual recorded applied values from the as-applied maps created by the applicator at the time the nitrogen was applied. Using these values instead of the target rates accounted for any applicator error. A fitted polynomial line was applied to each graph, and the x-value of the maximum point of the line was determined to be the optimum nitrogen rate for that zone. Three of the zones were removed from the analysis because the r-squared values of the response curves were less than 0.8.

Once optimum rates were determined, the results of the prediction methods for each zone were compared to the optimum nitrogen rates for each zone, using a single-factor analysis of variance test with $p \leq 0.05$ for a conclusion of a significant difference (Webb & Pajak, 2013). Microsoft Excel and R statistical software were used to complete the analysis. The following prediction methods were used in this study:

- The Ohio State University New Nitrogen Recommendations (OSU New) – These are the current guidelines recommended for use in Ohio and developed by The Ohio State University Extension. The guidelines are based on past testing history by University researchers to calculate a predicted economic optimum rate based on previous crop, the value of corn, and the cost of nitrogen.

- Tri-State Fertility Recommendations – These were developed by The Ohio State University, Michigan State University and Purdue University and calculate nitrogen rates based on previous crop and farmer-defined yield goals.
- Brookside Labs Potential Nitrogen Analysis (PNA) – This is a fairly new soil test developed by Brookside Labs and is used to determine a nitrogen rate based on farmer-defined yield goals, nitrate and ammonium content of soil at time of application, organic matter content of soil, and microbial activity of the soil measured in a 24-hour incubation period.
- Pre-Sidedress Nitrogen Test (PSNT) – A soil test that measures the amount of nitrate and ammonium present in the soil at the time of application.
- Normalized Yield – This value was determined by calculating the average normalized yield value for each test zone.
- Estimated Crop Removal – This value was calculated by multiplying the farmer-defined yield goals by 0.9 pounds of nitrogen per bushel of corn. This is based on the fact that every bushel of corn is made up of 0.9 pounds of nitrogen (Silva, 2011).

While not a prediction method, 2013 yields were evaluated in the same way as the above prediction methods to determine the relationship between optimum nitrogen rate and yield. The yield value for each zone was calculated by averaging the yields for each of the check strips.

In addition, the use of normalized yield values as a predictor of future yield was evaluated. Even though every effort was made to ensure consistent field conditions across test zones, there was still some variability within each test zone. In order to overcome this variability in the analysis of normalized yield as a predictor of yield, the normalized yield value of each individual check strip was compared with the 2013 yield value of each check strip.

Results

Overall, optimum rates for each test zone ranged from 118 to 218 pounds of nitrogen per acre, and the overall optimum rate for all test zones was 170 pounds of nitrogen per acre (see figure 2). Response curves for each test zone can be found in Appendix B.

Of all of the prediction methods tested, only the PSNT showed a significant relationship between test values and optimum rate. Soil nitrate levels demonstrated a negative correlation to optimum rate with a p-value of 0.002, and soil ammonium levels demonstrated a positive correlation to optimum rate with a p-value of 0.032.

The only other significant correlation found was between 2013 yields and optimum rate. This was a negative correlation with a p-value of 0.0142 (see figure 3).

Normalized yield values were found to have a significantly positive correlation with 2013 yields with a p-value of 0.00505 (see figure 4).

Scatter plots for all of the comparisons between prediction methods and optimum rates can be found in Appendix C.

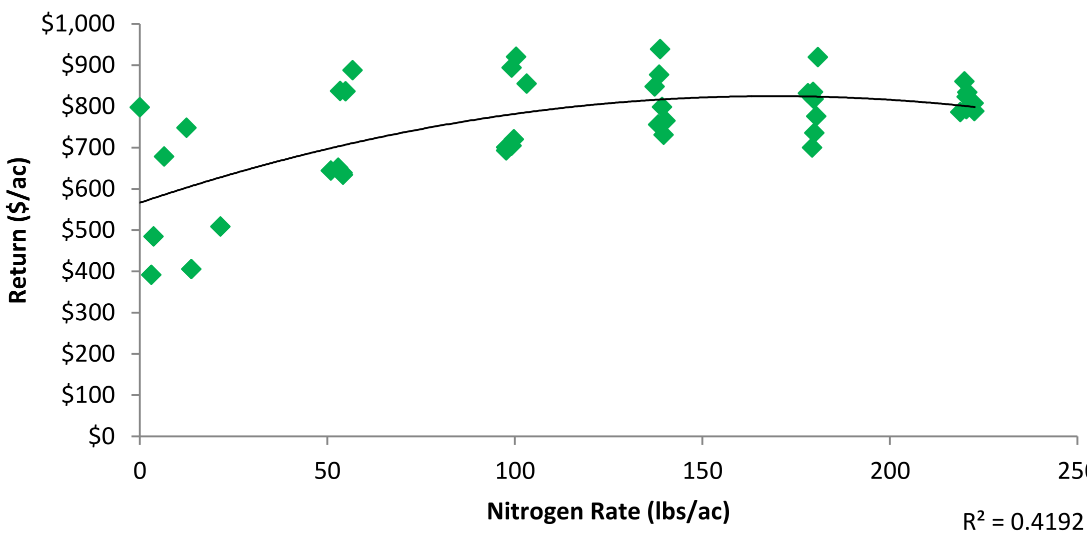

Figure 2: Scatter plot of application rates and return values for all test strips evaluated. A polynomial fitted line was used to determine the overall optimum rate at 170 lbs/ac.

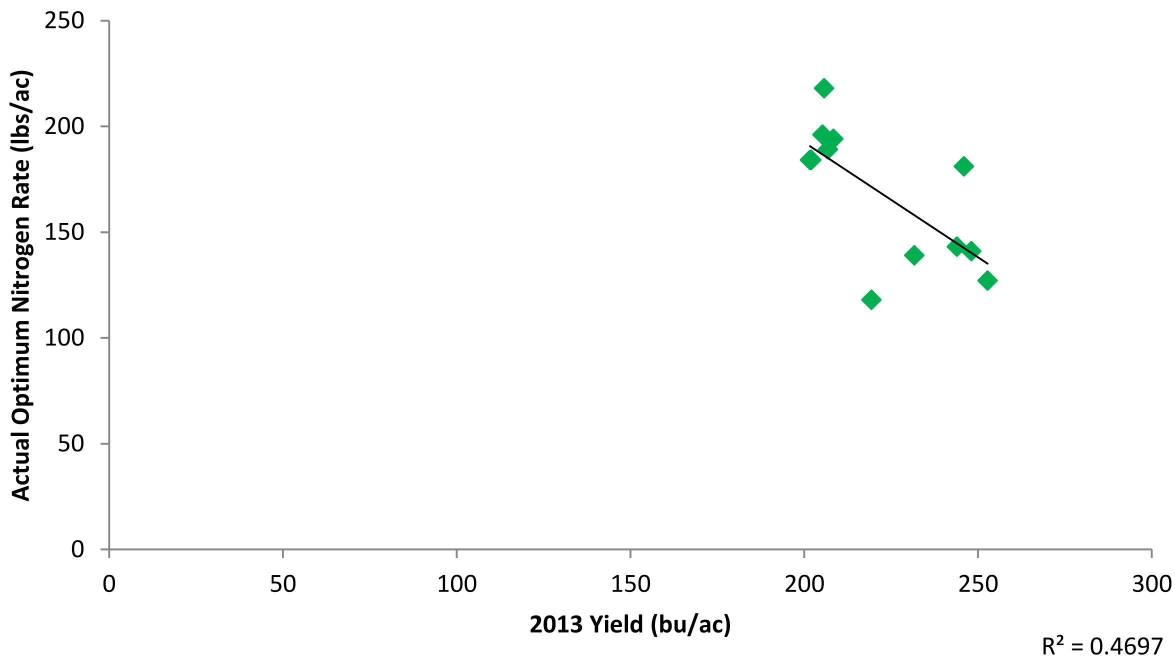

Figure 3: Scatter plot of average zone yields and optimum rate values, indicating a negative correlation. The p-value for this relationship was 0.0142.

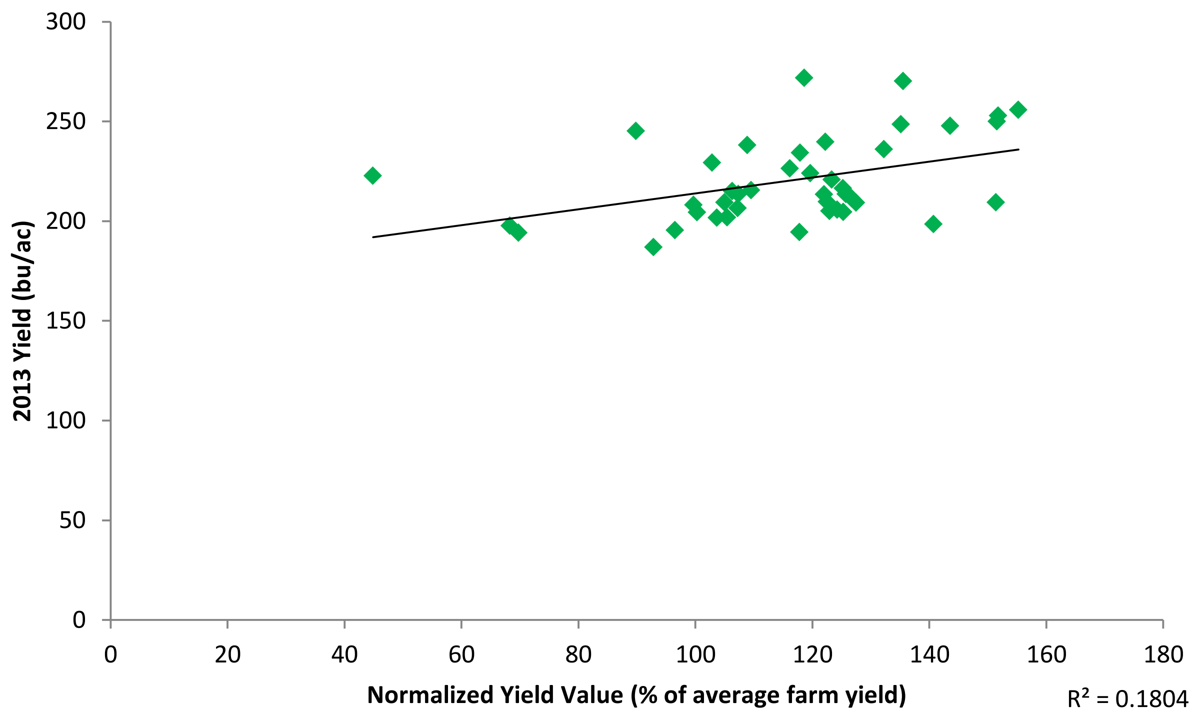

Figure 4: Scatter plot of normalized yield values (based on yield history from 2009-2012) and 2013 yield values for each check strip in all test zones, indicating a positive correlation. The p-value for this relationship was 0.00505.

Discussion

The results of this study indicate that there is potential for variable-rate technology to be utilized in nitrogen application, as can be seen by the wide range of optimum rates. However, the analysis of prediction methods demonstrated that predicting the optimum rate is difficult, yet necessary to make variable-rate applications effective.

The PSNT showed some promise in its ability to predict yields. However, even though the relationship was significant, at a given PSNT value, there is a wide range of optimum rates (see figures 33 and 34 in Appendix C). PSNT also comes with significant cost, both in time for collecting samples and lab analysis costs.

While the 2013 yields are significantly correlated to the optimum rate of nitrogen, they are not very helpful in themselves because they aren't known until after the crop is harvested. However, the yields can be helpful because they demonstrate that if yield can be predicted, then optimum nitrogen rate can be predicted.

There was not a significant relationship between normalized yield values and optimum rates for each test zone, however, the variability of normalized yield within each test zone cannot be ignored. In order to account for this variability, normalized yield was evaluated as a predictor of yield, rather than as a predictor of optimum rate. When evaluated this way, normalized yield had a strong relationship with actual yield, indicating that normalized yield values have the ability to predict future yields. Therefore, this normalized yield method (using normalized yields to predict future yields) can be used as a means of predicting optimum nitrogen rate.

Using these relationships, it can be concluded that a higher rate of nitrogen should be applied to areas of the field with lower relative productivity, and a lower rate of nitrogen should be applied to areas of the field with higher relative productivity, with relative productivity being determined by normalized yield history. However, this study is significantly limited in that it only evaluates data from a limited number of plots for one year. These conclusions are also not applicable to areas of a field that have severe limitations, such as a sand ridge or poor drainage, as these types of limitations were not evaluated in this study. In order to determine more precise nitrogen rates that should be applied based on normalized yield, further testing is needed.

While the PSNT and normalized yield method appear to be equally capable of predicting optimum rates, there are other factors that must be considered when selecting which method to use. Many farmers have several years of yield data already available. Therefore the only cost to the normalized yield method of predicting nitrogen rates is the time needed to analyze normalized yield maps. This cost is much less than that of the PSNT, primarily because there is no lab analysis cost, but also because the PSNT soil samples must be collected in the spring when many other farm tasks need to be completed. This makes the opportunity cost of time for PSNT much greater than the normalized yield method, because the normalized yield maps could be analyzed in the winter when fewer farm tasks need to be completed. Therefore, while PSNT shows some promise, its comparable accuracy to the normalized yield method may not justify the additional costs of the test. It must be noted that there may be a specific situation in which the PSNT would be more beneficial than the normalized yield method, such as when manure is applied or significant nitrogen carryover from the previous year is expected (Mullen, 2009). However, this study did not evaluate those scenarios.

In order to utilize these conclusions in developing variable-rate nitrogen prescriptions, there must be a method to determine exact application rates. While this study may not provide conclusive evidence on how to determine exact rates, it does show a potential set of guidelines that can be used. Even though there was not a significant correlation between the OSU new recommendations and optimum rate, the recommended rates came very close to the actual optimum rate when all sites were averaged together. The average OSU new recommendation across all twelve test zones was 169 pounds per acre, and the optimum rate across all twelve test zones was 170 pounds per acre. Since these recommendations were designed to predict the average optimum rate across the state, they seem to be effective in that they came very close to predicting the overall optimum rate in this study. Therefore, the OSU new recommendations could be used as a starting point in developing variable-rate nitrogen prescriptions.

Once the OSU new recommendation is determined, variable-rate prescription could be made using that recommendation as a starting point for a zone with average productivity. Then the normalized yield method could be used to adjust rates up or down for other zones based on yield potential, with higher rates applied to lower productivity areas and lower rates applied to higher productivity areas. While this study does not definitively support this method, it does indicate that there is potential for it to be used to create effective variable-rate nitrogen prescriptions. Further testing of the method is needed to determine its effectiveness.

Acknowledgements

I would like to thank Keith Hannewald for sponsoring the project and for his assistance in applying treatments and collecting data, Dr. James Metzger for serving as my research advisor, Dr. David Barker for assistance with statistical analysis, and Dr. Peter Thomison for assistance in experimental design.

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Appendix A: Normalized Yield Maps and Prescription Maps

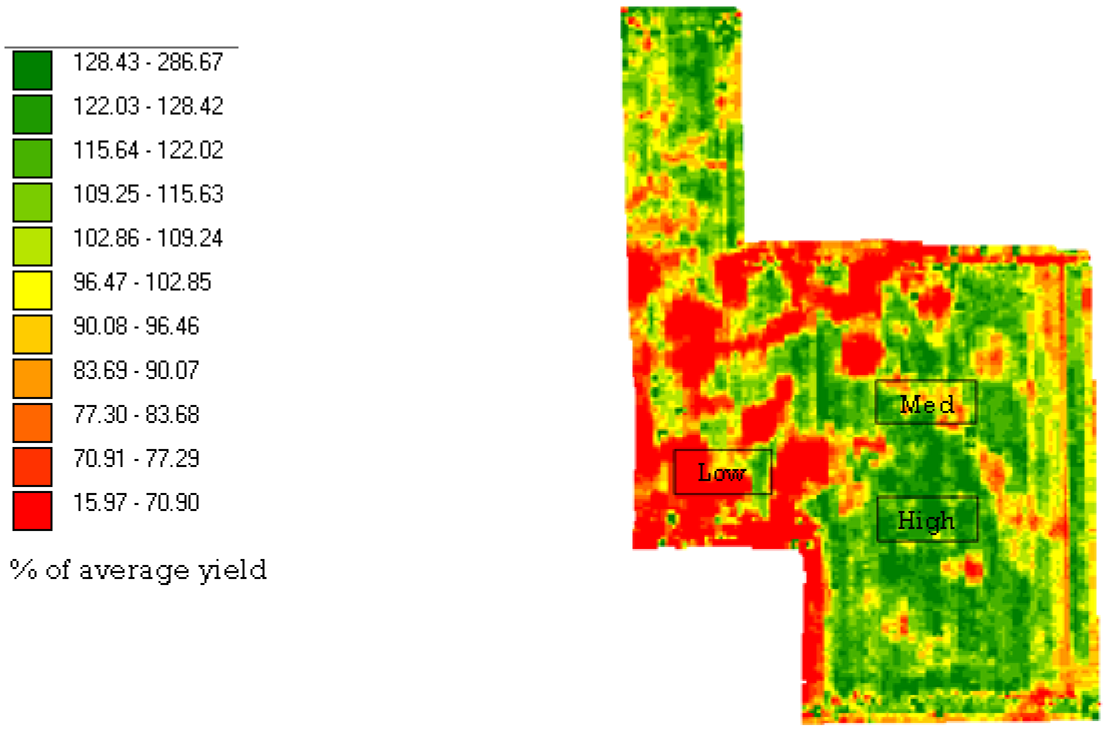

Figure 5: Field A (38.8 acres) – Normalized Yield Map

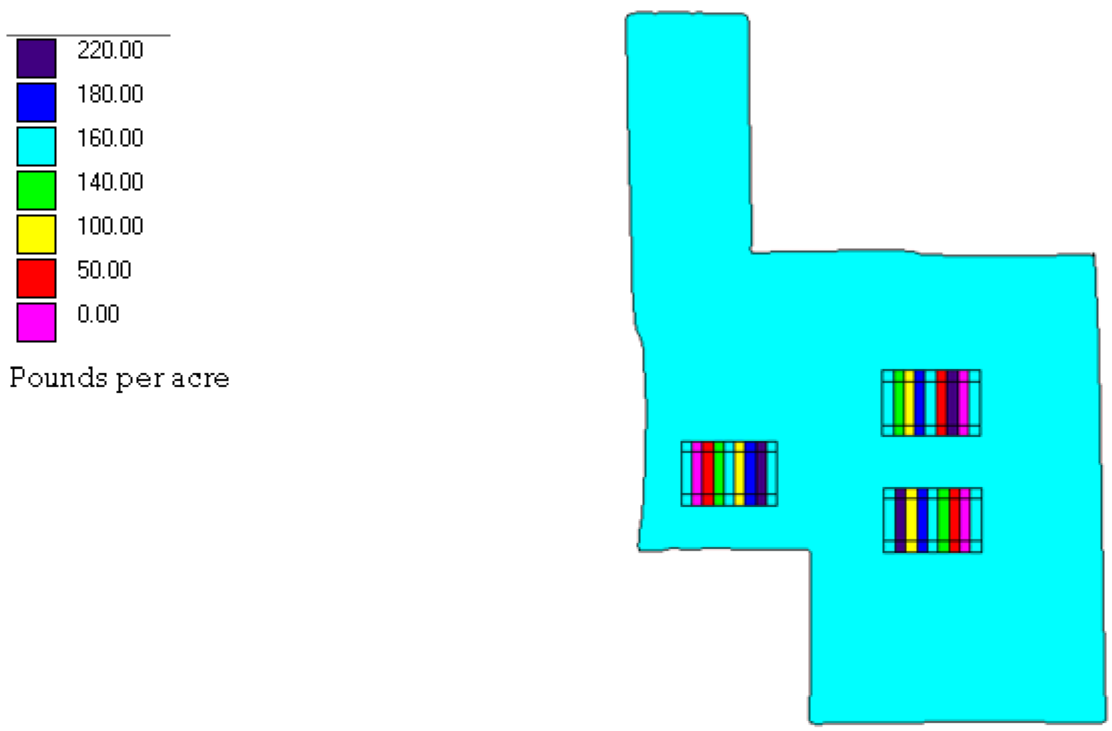

Figure 6: Field A (38.8 acres) – Variable Rate Prescription Map with Test Strips

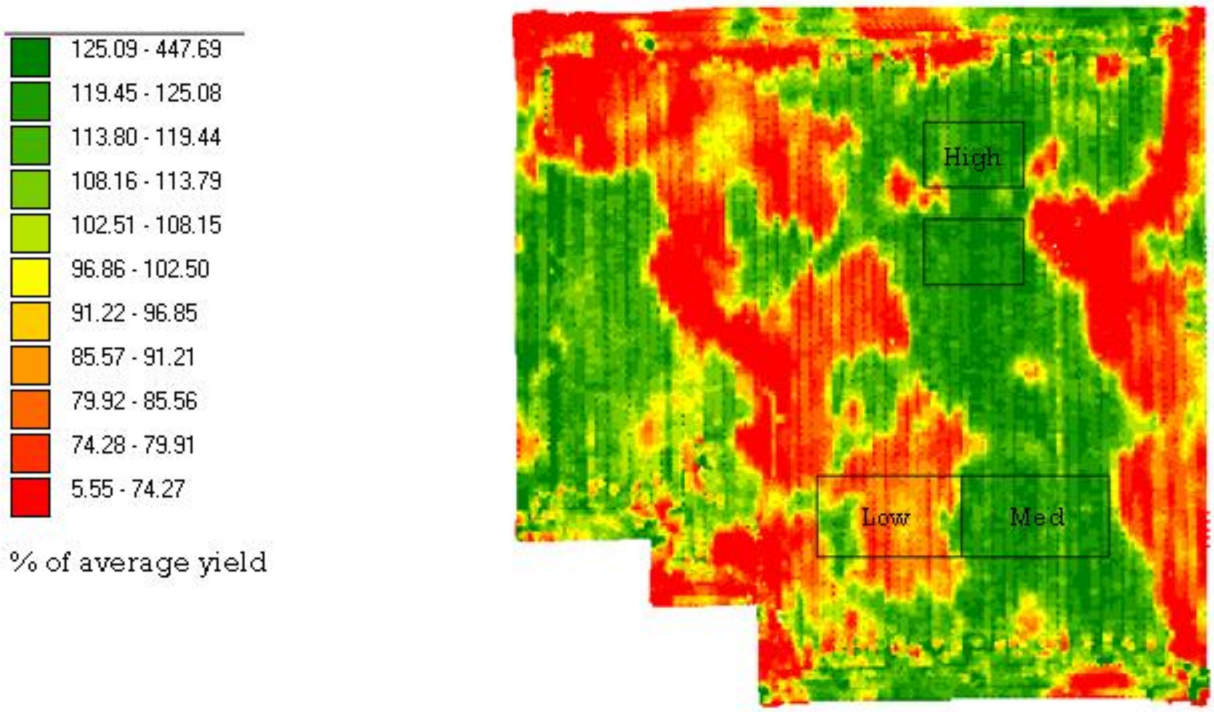

Figure 7: Field B (35.7 acres) – Normalized Yield Map

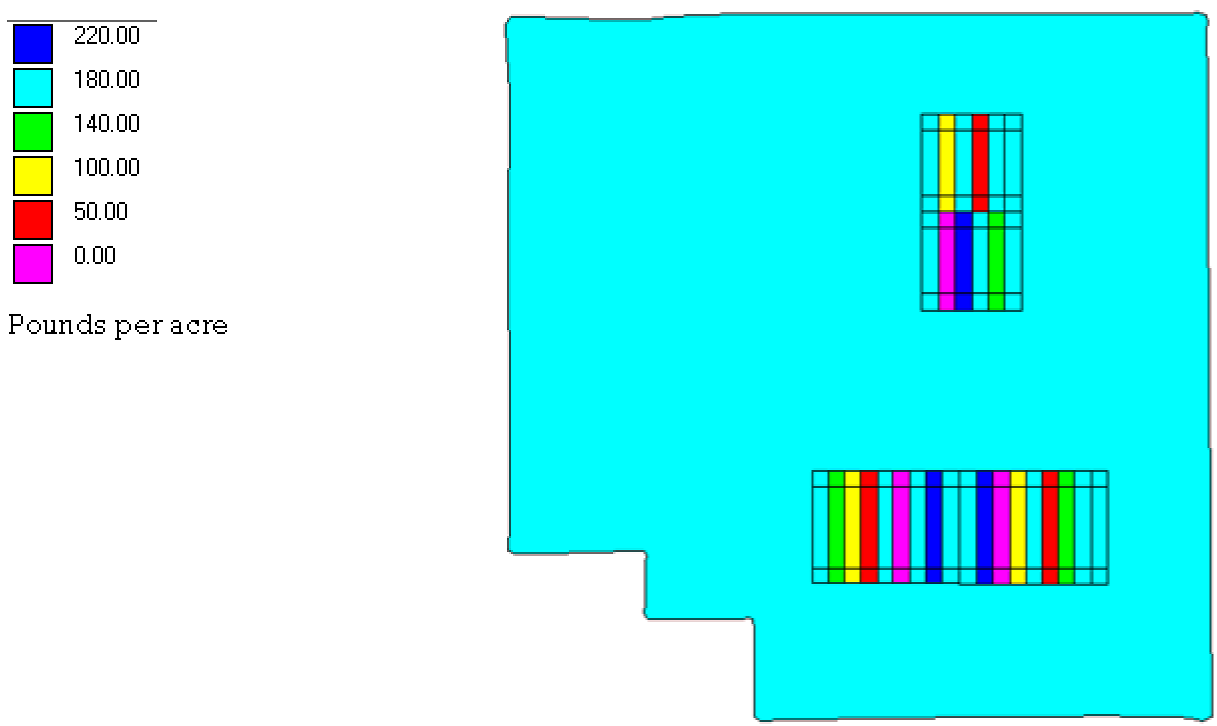

Figure 8: Field B (35.7 acres) – Variable Rate Prescription Map with Test Strips

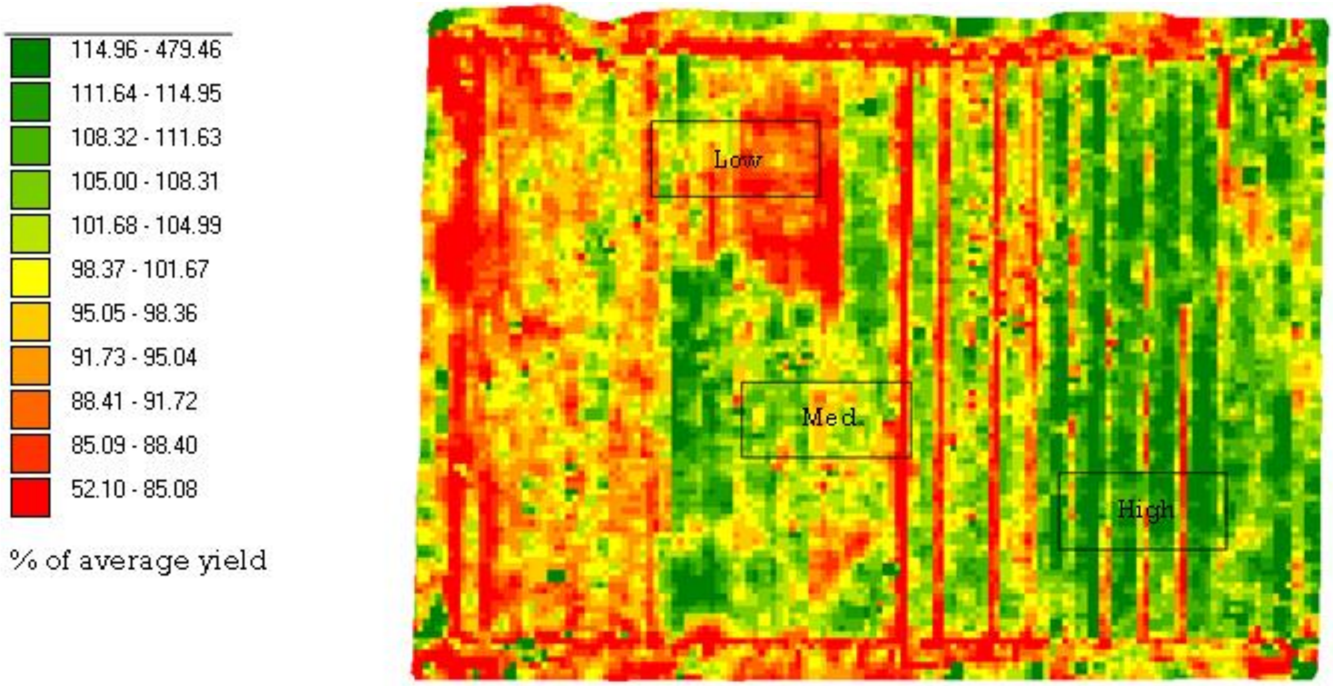

Figure 9: Field C (35.8 acres) – Normalized Yield Map

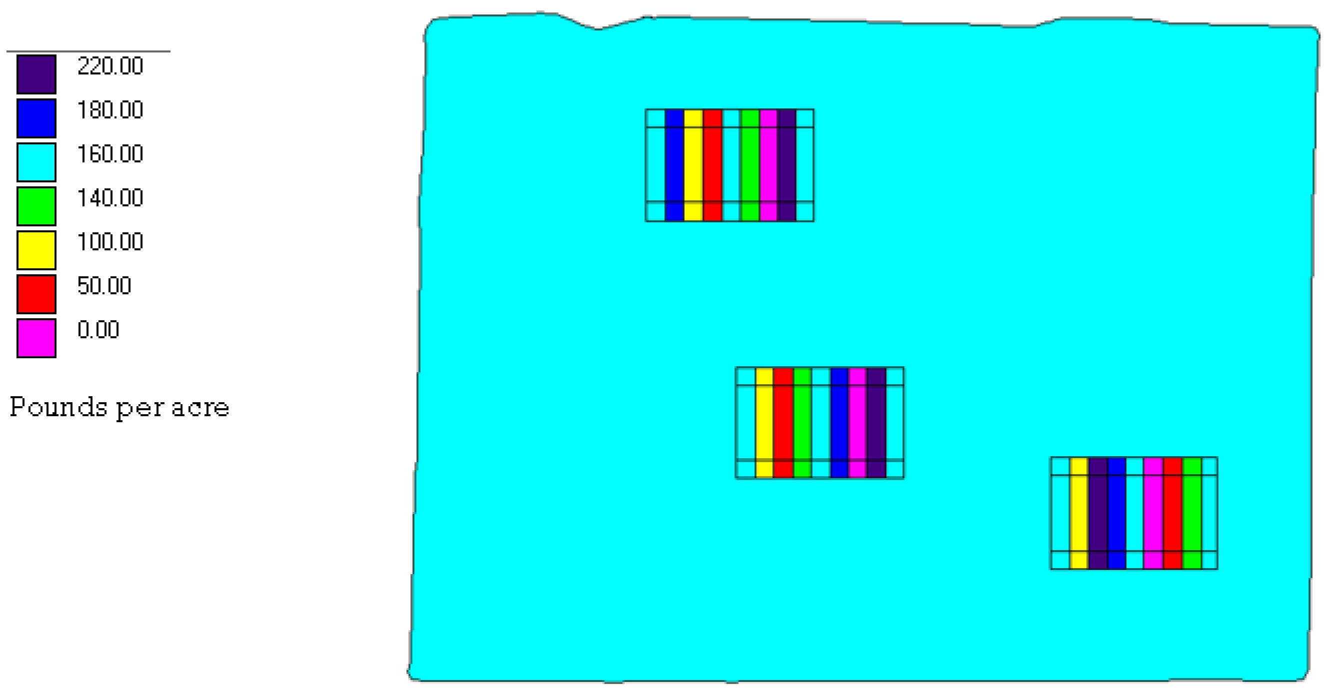

Figure 10: Field C (35.8 acres) – Variable Rate Prescription Map with Test Strips

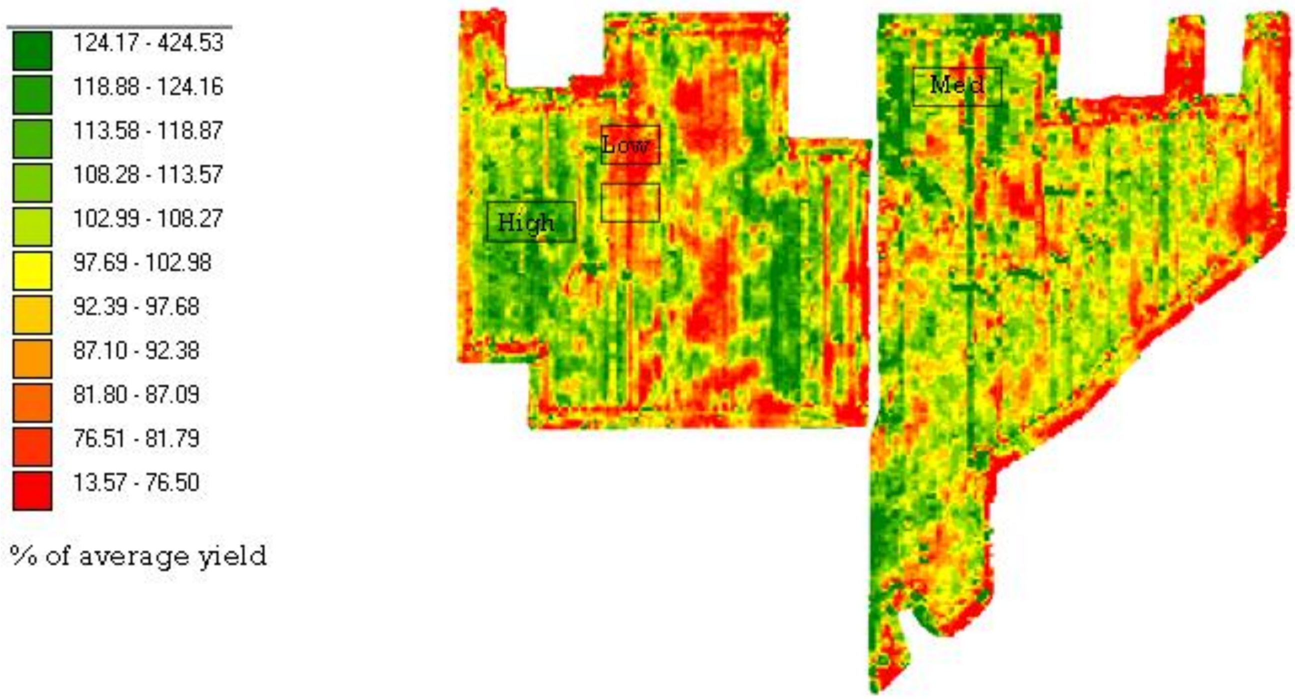

Figure 11: Field D (70.9 acres) – Normalized Yield Map

Figure 12: Field D (70.9 acres) – Variable Rate Prescription Map with Test Strips

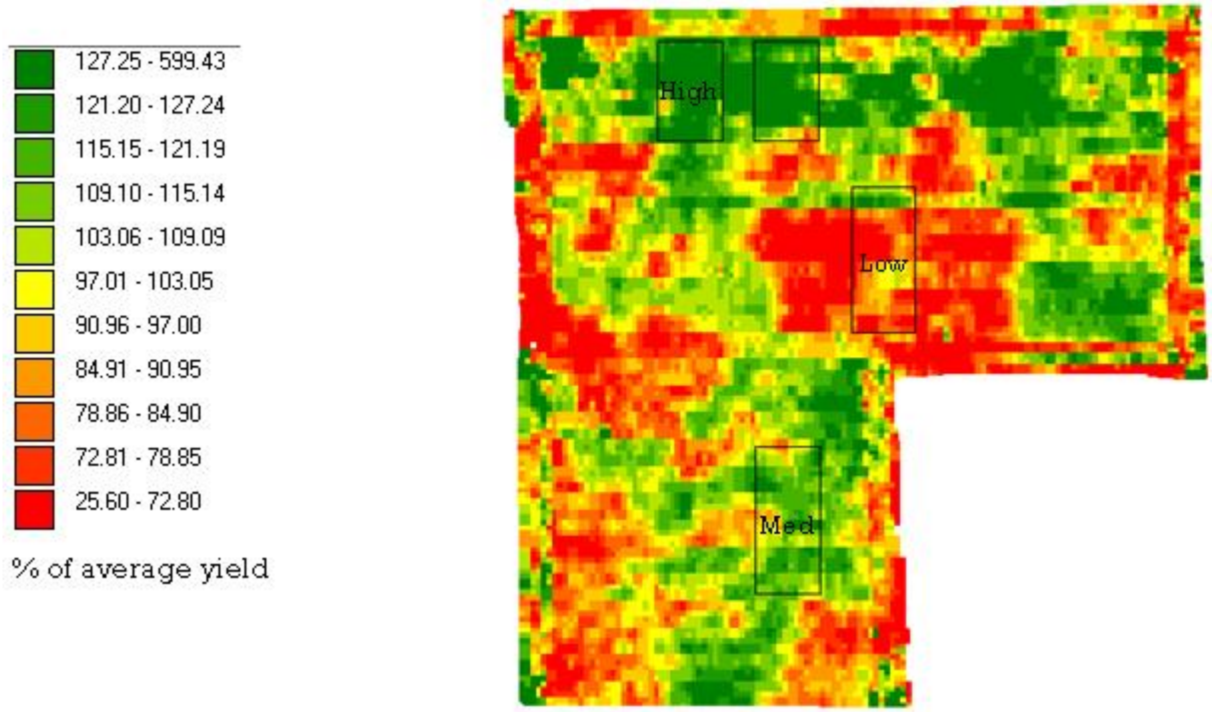

Figure 13: Field E (30.3 acres) – Normalized Yield Map

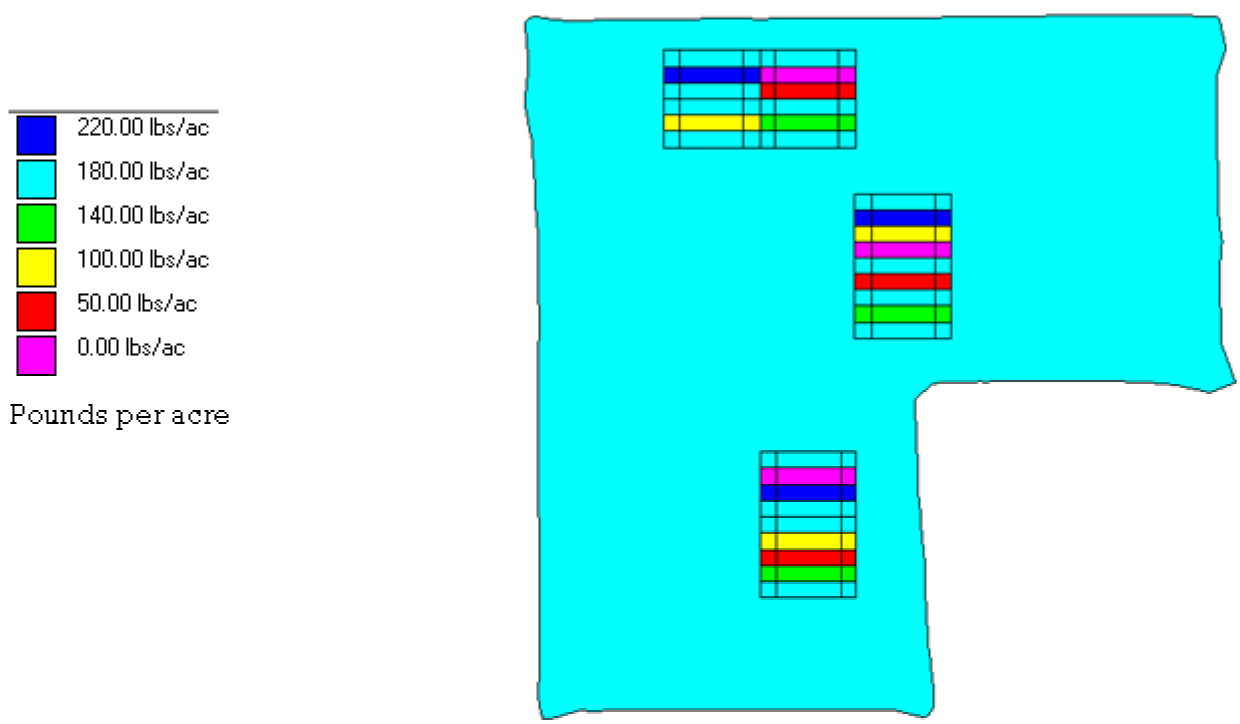

Figure 14: Field E (30.3) – Variable Rate Prescription Map with Test Strips

Appendix B: Response Curves

Table 2: Nitrogen Response at Field A - Low

ID	Field	App. Rate	Yield	Return
1102	Field A	16.7	106.0	$422
1103	Field A	50.1	189.1	$757
1106	Field A	99.3	239.3	$943
1104	Field A	142.1	247.4	$954
1107	Field A	180.0	258.0	$978
1108	Field A	221.8	276.9	$1,035
	Optimum Rate	**181**		

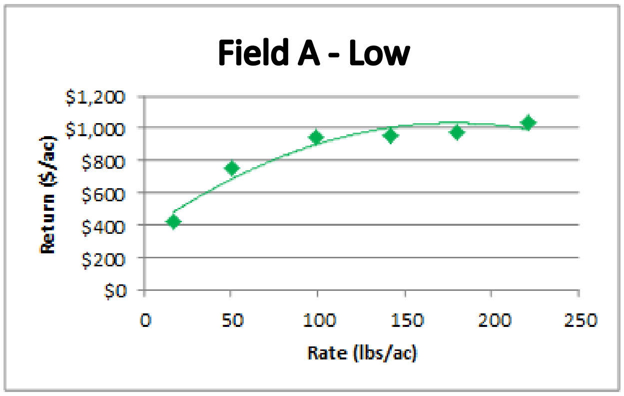

Figure 15: Response curve for the low productivity zone at Field A. R^2=0.9323

Table 3: Nitrogen Response at Field A - Medium

ID	Field	App. Rate	Yield	Return
1208	Field A	21.9	158.8	$644
1206	Field A	61.9	224.4	$900
1203	Field A	99.0	238.9	$941
1202	Field A	175.8	246.7	$932
1204	Field A	173.9	245.6	$929
1207	Field A	218.8	239.5	$878
	Optimum Rate	**143**		

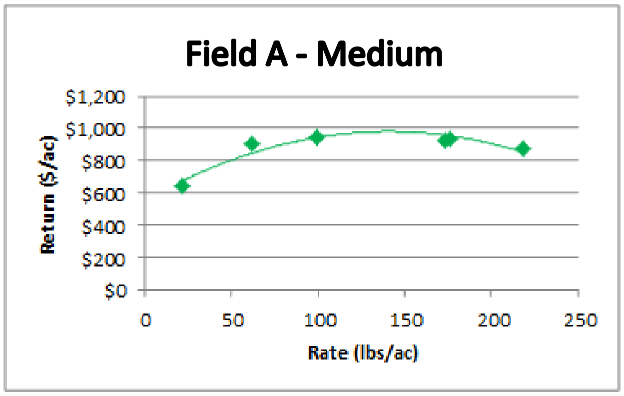

Figure 16: Response curve for the medium productivity zone at Field A. R^2=0.9067

Table 4: Nitrogen Response at Field A - High

ID	Field	App. Rate	Yield	Return
1308	Field A	9.9	207.6	$857
1307	Field A	49.0	233.9	$948
1303	Field A	98.6	252.6	$1,000
1306	Field A	140.5	246.0	$949
1304	Field A	181.0	256.6	$972
1302	Field A	175.5	252.6	$958
	Optimum Rate	**127**		

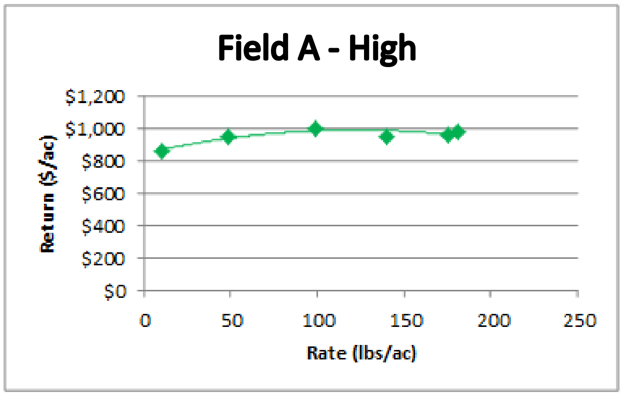

Figure 17: Response curve for the high productivity zone at Field A. R^2=0.8195

Table 5: Nitrogen Response at Field B - Low				
ID	**Field**	**App. Rate**	**Yield**	**Return**
2206	Field B	36.9	106.6	$410
2204	Field B	52.5	141.6	$551
2203	Field B	97.7	169.6	$645
2202	Field B	145.7	201.1	$752
2207	Field B	183.1	201.1	$732
2208	Field B	217.5	210.7	$753
	Optimum Rate	**184**		

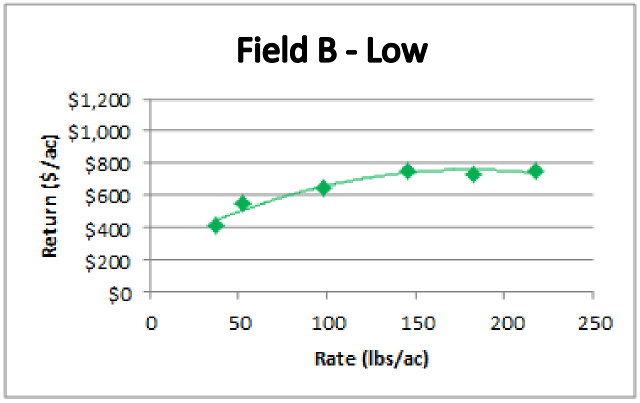

Figure 18: Response curve for the low productivity zone at Field B. R^2=0.9567

Table 6: Nitrogen Response at Field B - Medium				
ID	**Field**	**App. Rate**	**Yield**	**Return**
2303	Field B	23.2	149.5	$601
2306	Field B	62.7	140.7	$541
2304	Field B	98.8	207.9	$807
2307	Field B	148.2	209.9	$788
2308	Field B	179.8	216.3	$798
2302	Field B	220.7	216.9	$778
(not included in analysis due to R^2 < 0.8)				

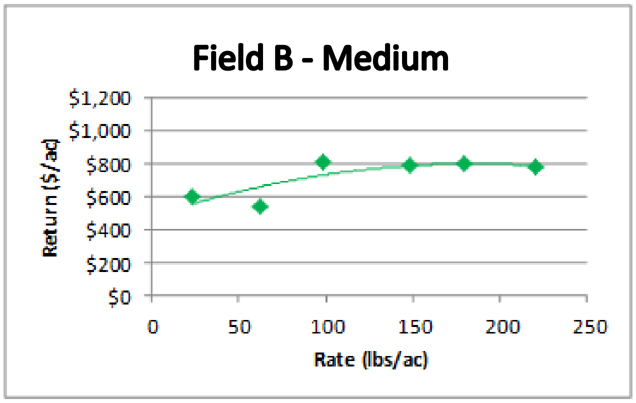

Figure 19: Response curve for the medium productivity zone at Field B. R^2=0.6741

Table 7: Nitrogen Response at Field B - High				
ID	**Field**	**App. Rate**	**Yield**	**Return**
2108	Field B	18.0	105.6	$416
2104	Field B	70.0	150.9	$581
2102	Field B	99.8	178.7	$682
2111	Field B	144.5	213.2	$804
2105	Field B	181.1	208.8	$766
2109	Field B	213.0	220.3	$797
	Optimum Rate	**198**		

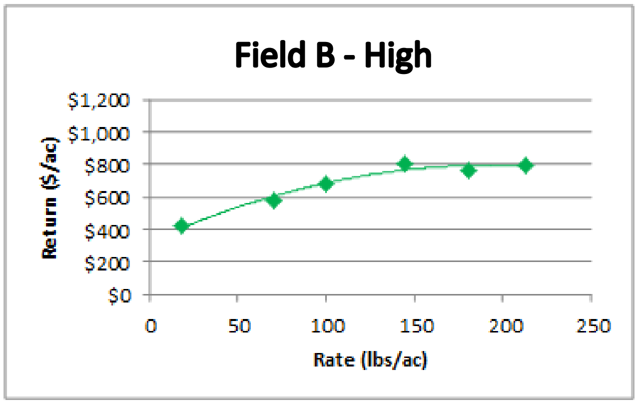

Figure 20: Response curve for the high productivity zone at Field B. R^2=0.9746

Table 8: Nitrogen Response at Field C - Low				
ID	**Field**	**App. Rate**	**Yield**	**Return**
3107	Field C	13.8	101.6	$405
3104	Field C	54.2	160.7	$634
3103	Field C	99.2	183.0	$704
3106	Field C	138.3	200.2	$755
3102	Field C	179.7	220.2	$817
3108	Field C	222.4	223.2	$807
	Optimum Rate	**194**		

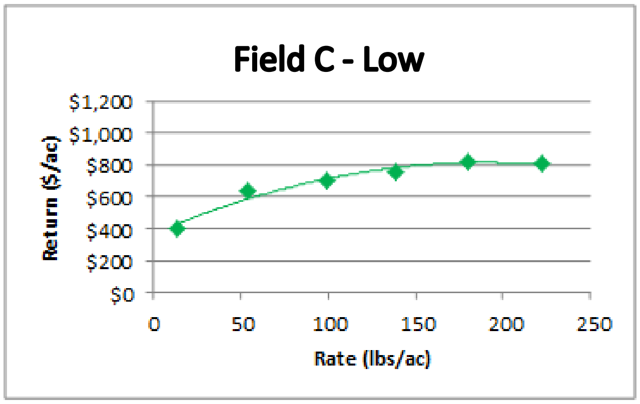

Figure 21: Response curve for the low productivity zone at Field C. R^2=0.9688

Table 9: Nitrogen Response at Field C - Medium				
ID	**Field**	**App. Rate**	**Yield**	**Return**
3207	Field C	11.8	200.5	$826
3203	Field C	50.7	220.5	$890
3202	Field C	98.2	224.4	$880
3204	Field C	139.7	234.3	$900
3206	Field C	181.4	233.0	$871
3208	Field C	218.6	250.8	$926
(not included in analysis due to R^2 < 0.8)				

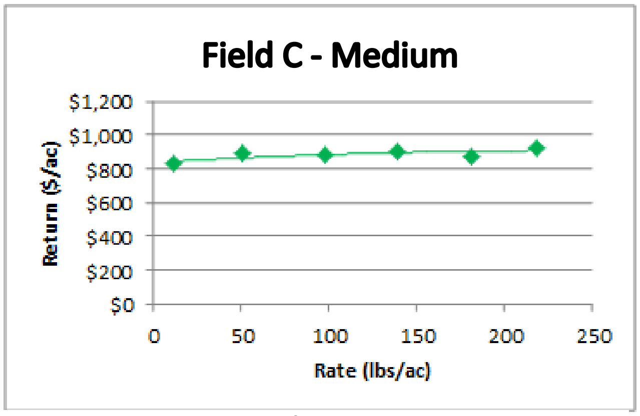

Figure 22: Response curve for the medium productivity zone at Field C. R^2=0.5612

Table 10: Nitrogen Response at Field C - High				
ID	**Field**	**App. Rate**	**Yield**	**Return**
3306	Field C	6.5	164.8	$678
3307	Field C	56.8	220.6	$887
3302	Field C	100.4	233.9	$919
3308	Field C	138.8	243.2	$938
3304	Field C	180.8	244.0	$918
3303	Field C	219.9	235.3	$860
	Optimum Rate	**141**		

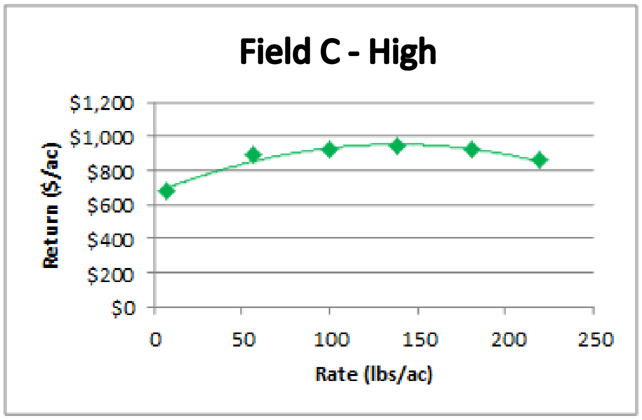

Figure 23: Response curve for the high productivity zone at Field C. R^2=0.9616

Table 11: Nitrogen Response at Field D - Low				
ID	**Field**	**App. Rate**	**Yield**	**Return**
4202	Field D	0.0	118.7	$485
4204	Field D	128.3	108.3	$370
4208	Field D	100.0	124.6	$455
4205	Field D	142.3	165.6	$606
4209	Field D	178.2	153.7	$536
4211	Field D	215.7	188.1	$662
(not included in analysis due to R^2 < 0.8)				

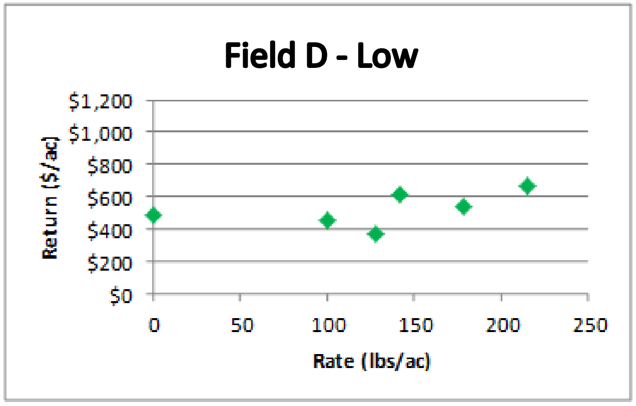

Figure 24: Scatter plot for the low productivity zone at Field D. A response curve could not be fit to the graph because of the irregularity of data in this zone.

Table 12: Nitrogen Response at Field D - Med.				
ID	**Field**	**App. Rate**	**Yield**	**Return**
4307	Field D	12.5	183.7	$747
4304	Field D	54.9	210.0	$836
4308	Field D	99.2	229.1	$893
4303	Field D	138.5	230.3	$876
4306	Field D	179.6	225.7	$834
4302	Field D	220.7	231.0	$834
	Optimum Rate	**139**		

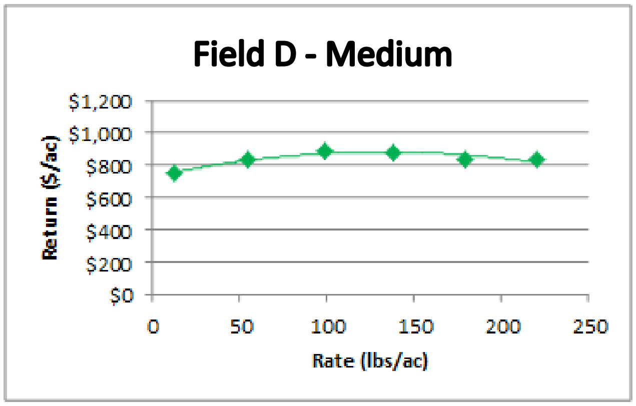

Figure 25: Response curve for the medium productivity zone at Field D. R^2=0.8605

Table 13: Nitrogen Response at Field D - High				
ID	**Field**	**App. Rate**	**Yield**	**Return**
4108	Field D	0.0	194.1	$797
4104	Field D	53.4	210.4	$837
4107	Field D	103.2	221.0	$854
4106	Field D	137.3	223.8	$848
4103	Field D	178.2	225.2	$831
4102	Field D	222.6	220.8	$788
	Optimum Rate	**118**		

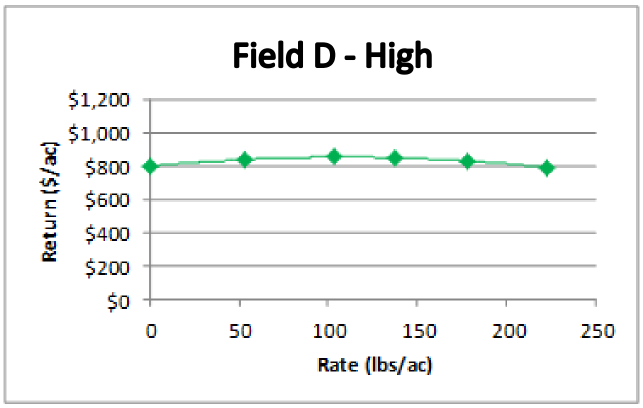

Figure 26: Response curve for the high productivity zone at Field D. R^2=0.9966

Table 14: Nitrogen Response at Field E - Low				
ID	**Field**	**App. Rate**	**Yield**	**Return**
5204	Field E	3.1	97.0	$391
5206	Field E	51.0	162.6	$643
5203	Field E	97.7	180.1	$692
5207	Field E	140.2	202.5	$764
5208	Field E	179.9	200.9	$735
5202	Field E	220.4	219.6	$793
	Optimum Rate	**184**		

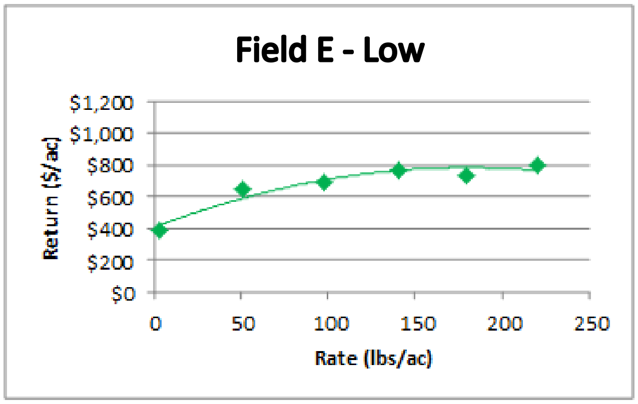

Figure 27: Response curve for the low productivity zone at Field E. R^2=0.9355

Table 15: Nitrogen Response at Field E - Medium				
ID	**Field**	**App. Rate**	**Yield**	**Return**
5302	Field E	3.7	119.0	$484
5307	Field E	54.1	161.7	$638
5306	Field E	97.7	181.9	$700
5304	Field E	139.3	210.4	$798
5308	Field E	180.4	210.3	$775
5303	Field E	220.5	226.7	$823
	Optimum Rate	**218**		

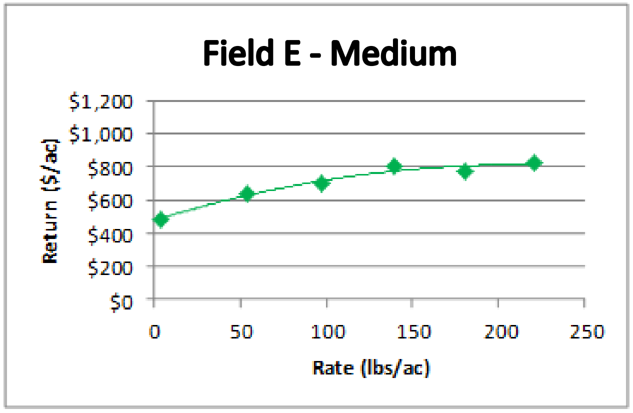

Figure 28: Response curve for the medium productivity zone at Field E. R^2=0.9749

Table 16: Nitrogen Response at Field E - High				
ID	**Field**	**App. Rate**	**Yield**	**Return**
5108	Field E	21.5	126.8	$508
5109	Field E	52.9	164.5	$651
5105	Field E	99.8	186.8	$720
5104	Field E	139.7	194.4	$730
5111	Field E	179.3	192.4	$700
5102	Field E	218.8	217.6	$785
	Optimum Rate	**196**		

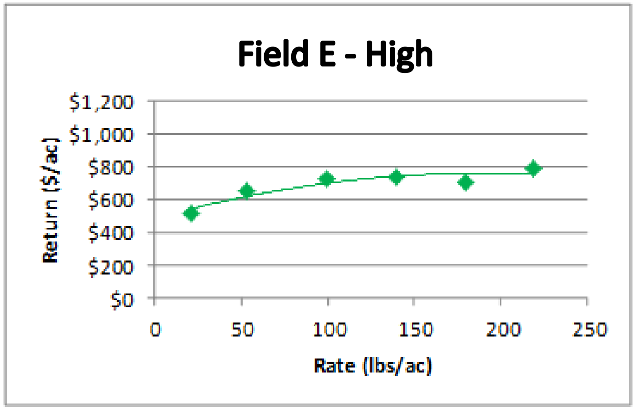

Figure 29: Response curve for the high productivity zone at Field E. R^2=0.8376

Appendix C: Prediction Method Comparisons

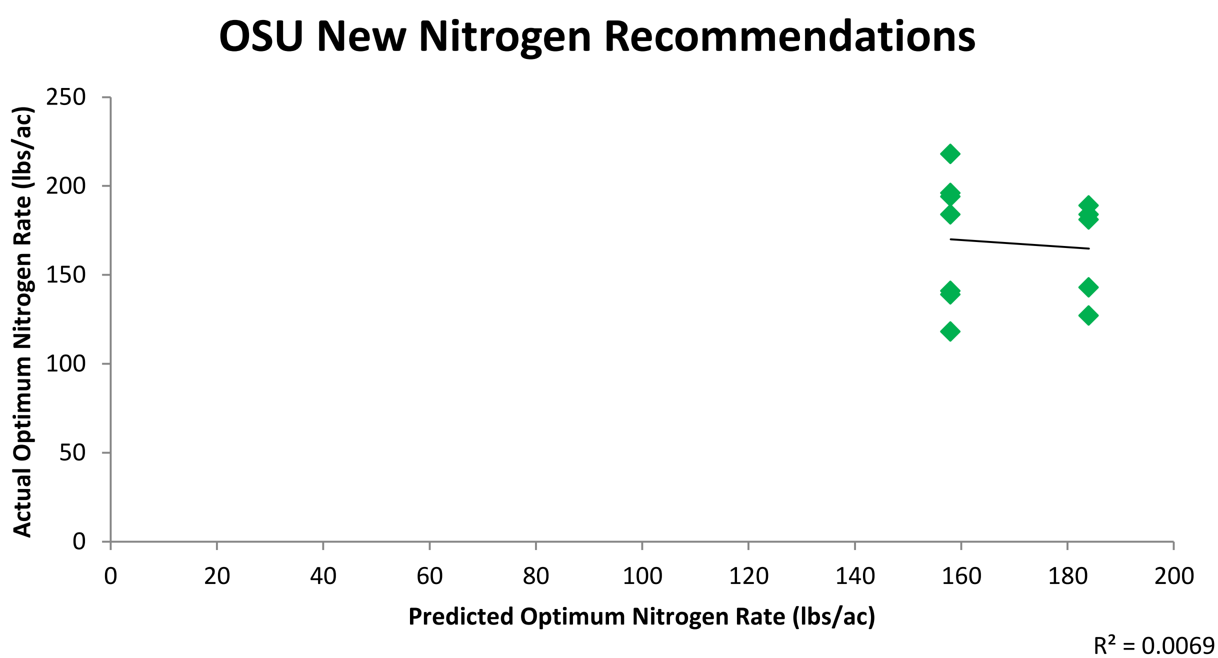

Figure 30: Scatter plot comparing predicted nitrogen rate by the OSU new recommendation system to actual optimum nitrogen rate, p-value=0.798.

Table 17: OSU New Recommendation Predictions				
ID	**Field**	**Site**	**Optimum**	**Predicted**
1100	Field A	Low	181	184
1200	Field A	Medium	143	184
1300	Field A	High	127	184
2100	Field B	High	189	184
2200	Field B	Low	184	184
3100	Field C	Low	194	158
3300	Field C	High	141	158
4100	Field D	High	118	158
4300	Field D	Medium	139	158
5100	Field E	High	196	158
5200	Field E	Low	184	158
5300	Field E	Medium	218	158
		Averages	**170**	**169**

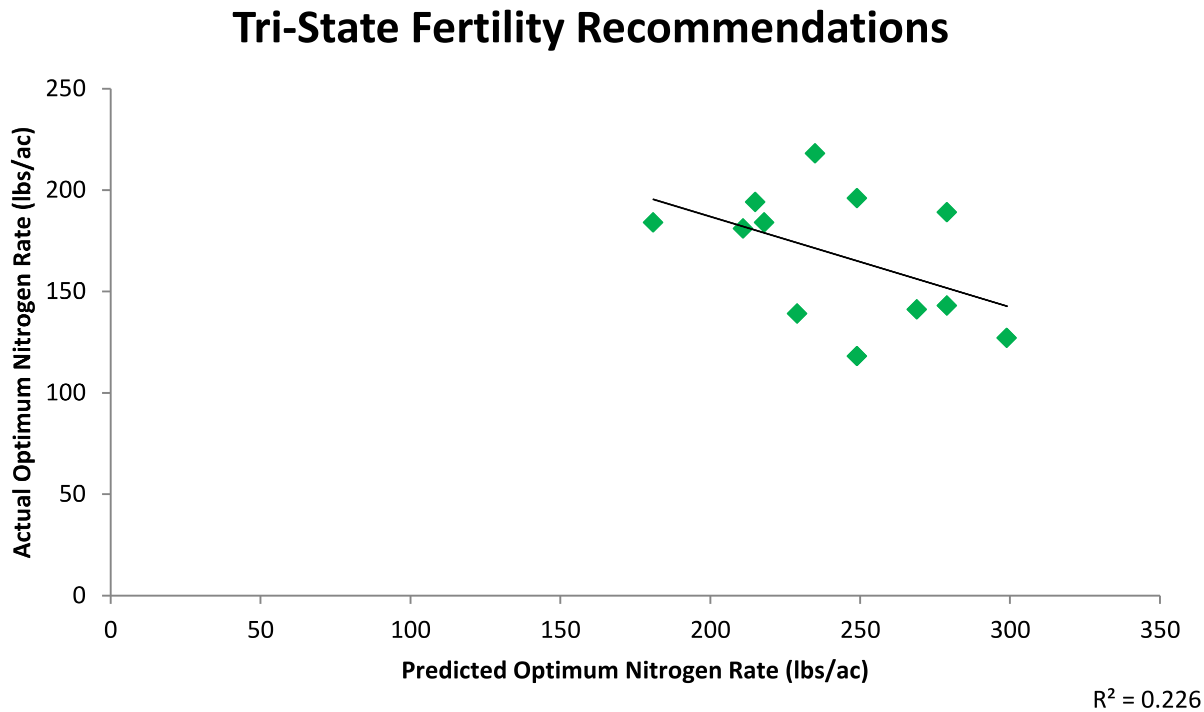

Figure 31: Scatter plot comparing predicted nitrogen rate by the Tri-State fertility recommendation system to actual optimum nitrogen rate, p-value=0.118.

Table 18: Tri-State Fertility Recommendation Predictions

ID	**Field**	**Site**	**Optimum**	**Predicted**
1100	Field A	Low	181	211
1200	Field A	Medium	143	279
1300	Field A	High	127	299
2100	Field B	High	189	279
2200	Field B	Low	184	218
3100	Field C	Low	194	215
3300	Field C	High	141	269
4100	Field D	High	118	249
4300	Field D	Medium	139	229
5100	Field E	High	196	249
5200	Field E	Low	184	181
5300	Field E	Medium	218	235
		Averages	**170**	**243**

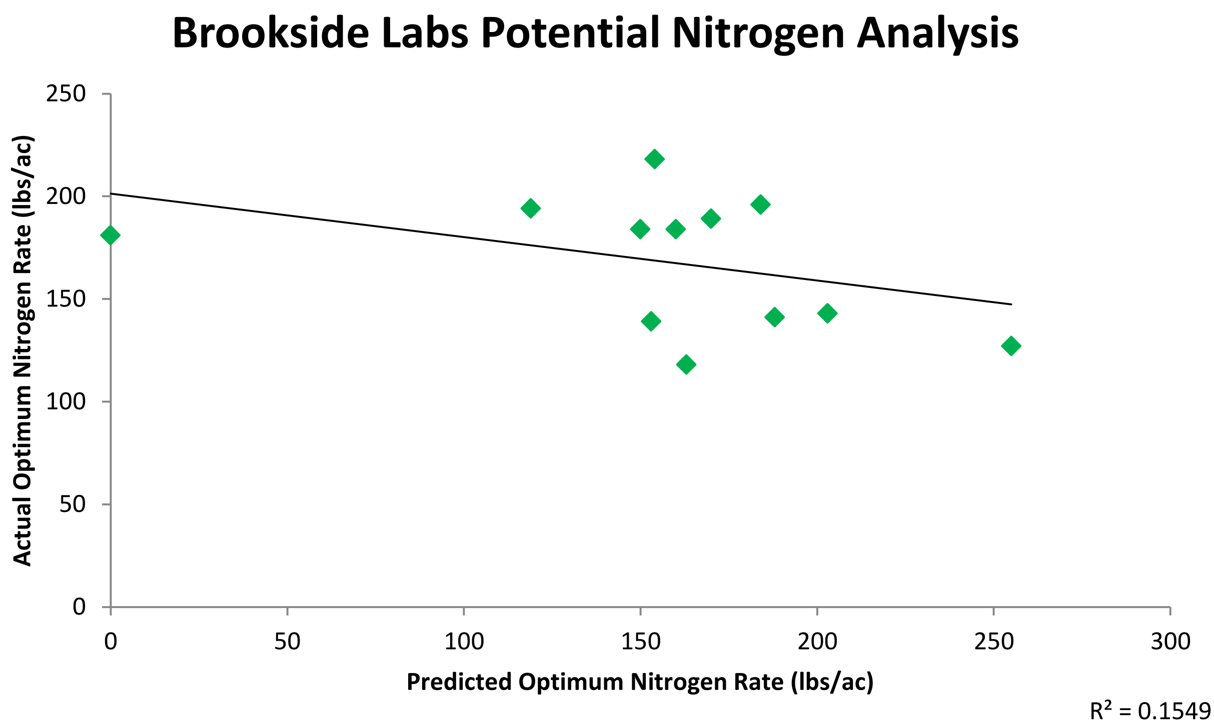

Figure 32: Scatter plot comparing predicted nitrogen rate by the Brookside Labs Potential Nitrogen Analysis to actual optimum nitrogen rate, p-value=0.206.

Table 19: Brookside Labs PNA Predictions				
ID	**Field**	**Site**	**Optimum**	**Predicted**
1100	Field A	Low	181	0
1200	Field A	Medium	143	203
1300	Field A	High	127	255
2100	Field B	High	189	170
2200	Field B	Low	184	150
3100	Field C	Low	194	119
3300	Field C	High	141	188
4100	Field D	High	118	163
4300	Field D	Medium	139	153
5100	Field E	High	196	184
5200	Field E	Low	184	160
5300	Field E	Medium	218	154
		Averages	**170**	**158**

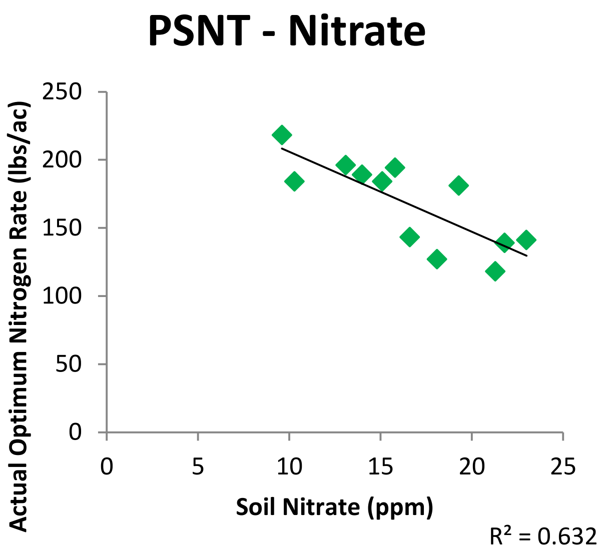

Figure 33: Scatter plot comparing soil nitrate concentration to actual optimum nitrogen rate, p-value=0.002.

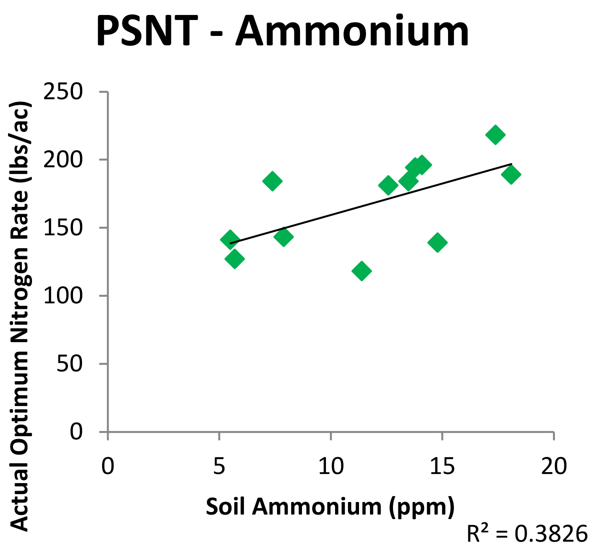

Figure 34: Scatter plot comparing soil ammonium concentration to actual optimum nitrogen rate, p-value=0.032.

Table 20: Pre-Sidedress Nitrogen Test

ID	Field	Site	Optimum	Nitrate	Ammonium
1100	Field A	Low	181	19.3	12.6
1200	Field A	Medium	143	16.6	7.9
1300	Field A	High	127	18.1	5.7
2100	Field B	High	189	14.0	18.1
2200	Field B	Low	184	15.1	7.4
3100	Field C	Low	194	15.8	13.8
3300	Field C	High	141	23.0	5.5
4100	Field D	High	118	21.3	11.4
4300	Field D	Medium	139	21.8	14.8
5100	Field E	High	196	13.1	14.1
5200	Field E	Low	184	10.3	13.5
5300	Field E	Medium	218	9.6	17.4

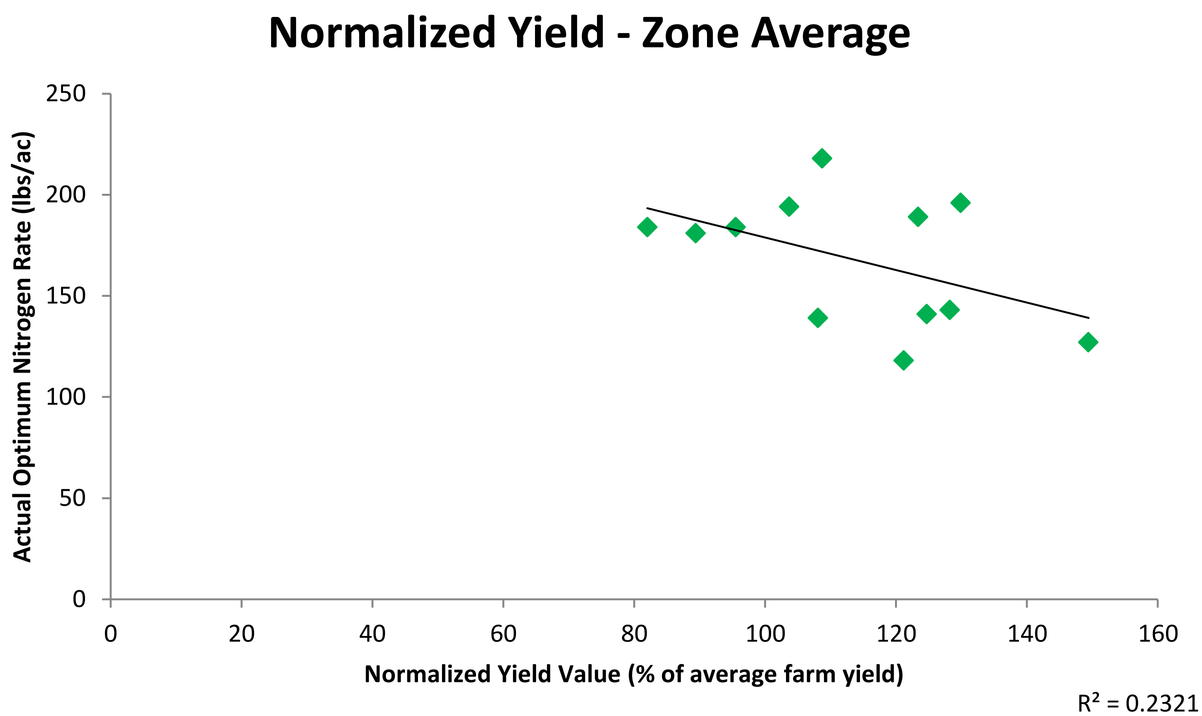

Figure 35: Scatter plot comparing the average normalized yield value for an entire test zone to actual optimum nitrogen rate, p-value=0.113.

Table 21: Normalized Yield Values

ID	Field	Site	Optimum	Normalized Yield Value
1100	Field A	Low	181	73.5
1200	Field A	Medium	143	105.3
1300	Field A	High	127	122.8
2100	Field B	High	189	122.1
2200	Field B	Low	184	94.5
3100	Field C	Low	194	92.3
3300	Field C	High	141	110.9
4100	Field D	High	118	114.6
4300	Field D	Medium	139	102.2
5100	Field E	High	196	135.0
5200	Field E	Low	184	85.2
5300	Field E	Medium	218	113.0

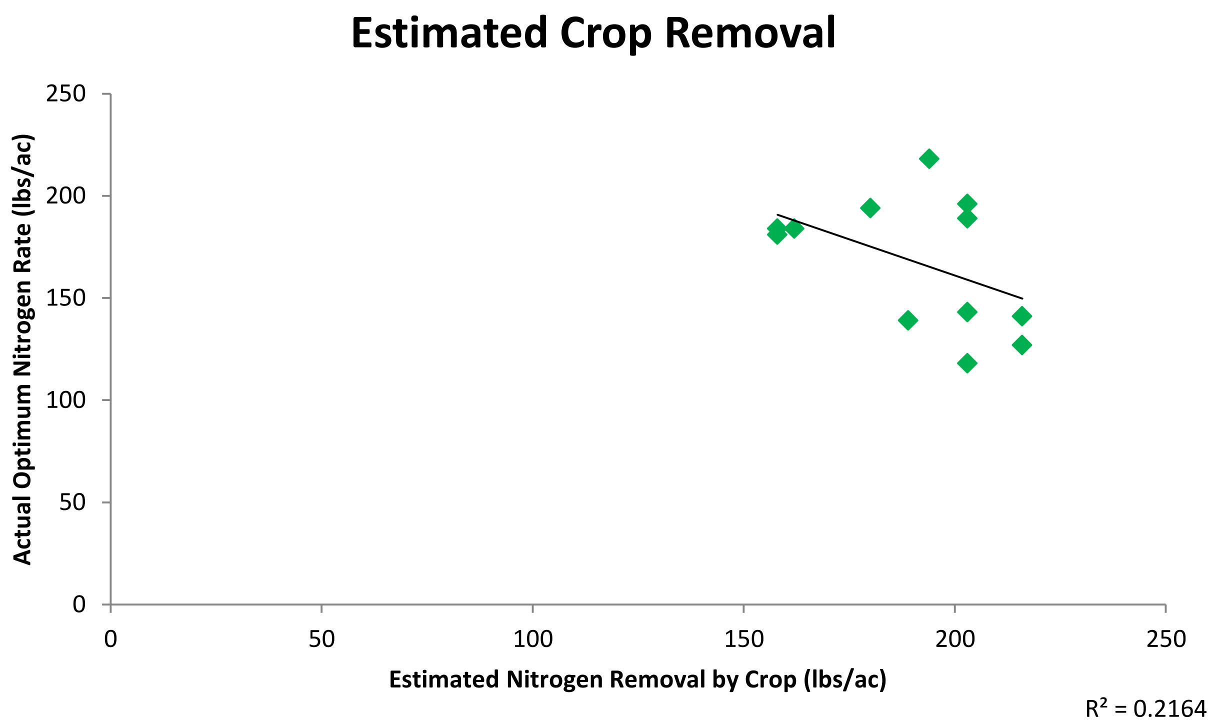

Figure 36: Scatter plot comparing predicted nitrogen rate by estimated crop removal to actual optimum nitrogen rate, p-value=0.128.

Table 22: Estimated Crop Removal Predictions

ID	Field	Site	Optimum	Predicted
1100	Field A	Low	181	158
1200	Field A	Medium	143	203
1300	Field A	High	127	216
2100	Field B	High	189	203
2200	Field B	Low	184	162
3100	Field C	Low	194	180
3300	Field C	High	141	216
4100	Field D	High	118	203
4300	Field D	Medium	139	189
5100	Field E	High	196	203
5200	Field E	Low	184	158
5300	Field E	Medium	218	194
		Averages	**170**	**190**